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TECHNICAL REPORT
70-32-CE

A REVIEW OF THE DEVELOPMENT OF BALLISTIC NEEDLE-PUNCHED FELTS

by

Roy C. Laible

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October 1969

UNITED STATES ARMY
NATICK LABORATORIES
Natick, Massachusetts 01760

U.S. ARMY MATERIEL COMMAND

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FOREWORD

Needle-punched felts have shown some promise in the area of ballistic resistance for 13 years. Although information has been available to the military and to the scientific community on some aspects of the ballistic resistance of needle-punched felts, there has been a need for a summary report, a void which this review attempts to fill. While the temptation is to emphasize only that information which can be explained and discussed definitively, this report takes a different approach, itemizing each of the factors influencing the properties of needle-punched felts and discussing not only our knowledge of these various factors but also areas requiring additional work. To accomplish this purpose better, the report is divided into sections concerned with all known fiber and fabrication parameters. Each of these parameters is then discussed individually and, when necessary, together with other closely interacting parameters.

It is hoped that this review will serve as an effective guide for future work in this area. The study was performed under Project Number 1T062105A329-02, Organic Materials Research for Army Materiel.

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ABSTRACT

As part of the continuing effort to improve ballistic materials for personnel armor, the fiber and fabrication parameters, dynamics of felt impact, and predictive equations attempting to connect ballistic resistance to known measurable parameters were reviewed for needle-punched felts. The ballistic resistance of needle-punched felts at low areal densities has been found to be superior to that of any other known material. On the other hand, at increased areal densities and against higher velocity missiles, other materials become competitive.

The extent to which needle-punched felts maintain their superiority to other materials at moderate areal densities is dependent upon certain fiber and fabrication properties. The highest tenacity polyamide fibers are currently the best available material. In fabrication, a relatively low degree of needling furnishes the best ballistic properties. In general, the thicker the felt that can be tolerated (at the same weight and areal density), the better the ballistic resistance. In addition, it is apparent that the level of ballistic protection varies depending upon the method of attaining the desired thickness.

The need is shown for additional work to determine the effect of fiber properties such as fiber denier, molecular weight, molecular weight distribution, and elongation upon the ballistic properties of the resulting felts. This work, in turn, will depend upon the availability of model fibers in which these parameters can be studied independently.

A REVIEW OF THE DEVELOPMENT OF BALLISTIC NEEDLE-PUNCHED FELTS

1. Introduction

As a result of the proved effectiveness of body armor in reducing combat troop casualties, the U. S. Army has supported research and development programs to improve ballistic resistant materials for personnel armor. The current Army standard fragmentation vest is an all-textile assemblage, of which the basic ballistic protective component is a twelve-layer, basket-weave, 14 oz/sq yd nylon duck weighing approximately 8-1/2 pounds per medium sized vest. The weight of this item clearly needs to be reduced without sacrificing protection.

As early as 1956, non-woven needle-punched felts offered significant ballistic protection as well as promise of significant weight savings over woven fabrics. The first military specification prepared in 1967 was for a felt which sacrificed about 20 percent in ballistic protection but was one-third the weight of the standard fabric assembly.

High areal density felts lose their advantage over standard fabric. Thus, at 18 oz/sq ft, which is the areal density of the standard fabric assembly, the ballistic protection of felt and fabric is essentially the same. At low areal densities, attained by using multiple layers of low density felt, it is possible to prepare felts at half the weight of the standard woven fabric vest while retaining 92 percent of its ballistic protection.

The mechanisms through which needle-punched felts defeat or react to a given missile are largely unknown. It is clear, however, that the mechanism is different from those operating in other materials such as woven fabrics, metals, ceramics and plastics. The mechanism of felt deformation appears to be highly dependent upon fiber-fiber friction, described as a "stick-slip" mechanism.

The ultimate level of ballistic protection theoretically, or even practically, attainable is difficult to ascertain. A systematic variation of each of the important parameters separately which affect the ballistic resistant performance of needle-punched felts is not possible experimentally at the present time. For example, it would be difficult to obtain experimental samples within a given class of polymers having systematically varied molecular weights for an investigation of structure-property relationships. It would also be a formidable venture to obtain these same materials, convert them into fibers, make them into felts, and measure their ballistic performance to relate the parameters of molecular weight and ballistic performance. As a result of this kind of difficulty, compromises were made between that which is desirable theoretically and that which is possible from a practical standpoint.

Despite experimental difficulties associated with the systematic study of needle-punched felts, efforts of the past 10 years have resulted in a wealth of information that has not been condensed and correlated. The purpose of this report is to digest and analyze the existing state of the art of needle-punched felts for ballistic applications and to predict and project the foreseeable future for this interesting class of materials.

This review is organized, so far as possible, to isolate the numerous parameters which individually or in combination could affect the ballistic performance of felt materials. From this analysis, many gaps in knowledge become apparent which illustrate the difficulties associated with the preparation of "the ideal felt."

Finally, the reader would hope for a standard test method, ballistic or mechanical, which would allow one to rate the felt materials in a definitive manner. Factors such as missile shape, spin and size can affect variations in ballistic response for different materials. This is a field of active study in military laboratories, but this information is not available for public dissemination at the present time. Most available information concerns tests with the 17-grain, .22 caliber fragment simulator, and the results of such tests will be used throughout this report as a measure of the comparative effectiveness of various felts.

2. Discussion

Most of the information available on felts is concerned with natural felts, felts which have incorporated a binder, or felts which have been heavily needle-punched. The important variable parameters associated with the preparation of needle-punched synthetic felts, especially as they might be related to ballistic resistance, have not been reported.

In this review, the influence of applicable fundamental fiber and fabrication parameters on ballistic resistant performance is examined. Each factor is treated separately so far as possible. This method makes it possible to isolate critical factors which need future work. It is also a useful method for a discussion and correlation of present and past felt studies. The factors to be considered in this review are tabulated (Table I) in two separate listings, one of the basic fibers, the other of fabrication parameters.

TABLE I

FIBER AND FABRICATION PARAMETERS

Fiber	Fabrication
1. Molecular Type	1. Type of Needling
2. Molecular Weight	2. Density of Needling
3. Tenacity	3. Angle of Needling
4. Molecular Weight Distribution	4. Crimped vs Uncrimped
5. Crystallinity	5. Length of Fibers
6. Draw Ratio	6. Thickness of Felt or Density of Felt
7. Elongation	7. Angle of Ply
8. Work-to-Break	
9. Fiber Surface	
10. Fiber Denier	

a. Fiber Parameters

(1) Molecular Type. The first report of the effects of variation in molecular type was published by Laible and Supnik[1] in 1964. A portion of this work is shown in Table II. The results indicate that the ballistic resistance of polyamide-type fibers is superior to that of the other fibers studied. Another polymer type, polypropylene, also appears worthy of consideration[1]. Despite the introductory nature of this work, additional studies by Ehlers[2] and Keith[3] confirmed these findings in hundreds of carefully conducted tests. The types studied included acrylic, modacrylic, polyester, cellulose acetate, rayon, polyvinyl alcohol, polypropylene, and polyamide fibers. The same conclusion was reached, namely, that polyamide fibers performed best and that polypropylene was an interesting second choice.

No attempt was made in the first study[1] and little effort was expended in the next two studies[2,3] to optimize the ballistic resistant performance of each fiber type. It is probable that by appropriate application of the other principles to be discussed, the performance of some of the fibers studied could be improved so that they would be competitive with the polyamides. At the present time, however, it would appear that the inherent nature of the polyamide structure makes it the most desirable from a structural point of view, at least of these structures evaluated to date. In specialized applications, such as the preparation of felts which were buoyant vests as well as protective, the use of treated fine denier acrylic fibers has been advocated[4]; however, it has been the experience of the authors that these buoyant vests are never ballistically equivalent to the polyamide felts. The second place listing of polypropylene may be confirmed by the fact that a combination of polypropylene felt, foam and nylon fabric has appeared as a Navy flotation vest with ballistic protective qualities[5].

It is interesting to note that naturally occurring polypeptides have been shown to have extremely high strengths[6]. Although sufficient spider silk has not been available for the preparation of a felt, work on individual spider silk filaments shows several points of interest. Extremely high strengths are found, especially in filaments from the Nephila Clavipes species. The stress-strain curves for spider silk filaments exhibit quite different behavior than that characteristic of the usual high strength synthetics. The stress-strain curve in Figure 1, for example, illustrates not only high strength and high elongation, but a differently shaped stress-strain curve, indicating that a different mechanism is operating in these materials which conceivably could lead to felts with improved energy-absorbing abilities. One does not necessarily conclude that spider silk should be incorporated in felts, but rather, that it is an interesting model material, showing that synthetic polypeptide fibers might have promise.

TABLE II

FIBER BATTS VERSUS BALLISTIC PROPERTIES

Material	Areal Density (of tested sample) oz/ft^2	Ballistic Limit (Velocity) ft/sec (17-grain simulator)
Acrylic-1 (1 layer)	3.4	634
Modacrylic (1 layer)	3.4	695
Polyethylene (1 layer)	3.4	553
Polypropylene (1 layer)	3.4	898
Nylon (1 layer, 0.11-in. thick)	2.2	798
Nylon (2 layer, 0.22-in. thick)	4.4	1050
Nylon (3 layer, 0.33-in. thick)	6.6	1139
Nylon (1 layer, 0.60-in. thick)	6.3	1070
Nylon (commercial felt, 1 layer, 0.50-in. thick)	6.3	914

(2) Molecular Weight. The molecular weight of commercially available polyamide fibers has increased from about 10,000 20 years ago to 21,000 today, the latter figure representing the high-strength tire cord presently available. The effect of molecular weight variations upon the ultimate ballistic resistance of felts and fabrics is closely related to another parameter, tenacity. As the molecular weight of polyamide fibers increased throughout the years, so did the strength.

It should be noted that beyond a certain level of molecular weight, increasing increments of molecular weight will yield progressively decreasing increments of strength and/or ballistic resistant advantage. In fact, beyond some limit of molecular weight, entanglements will hinder the spinning and subsequent drawing operations and a poorer product will result. The problem is to determine this endpoint and to reduce the molecular weight until the optimum is achieved.

(3) Tenacity. Tenacity is strength related to a linear density, when the linear density is unity on the basis of a weight of one gram for 9,000 meters in length of fiber. Relating strength to a linear density rather than to cross-section makes it possible to compare different fibrous materials on a weight basis. Since the importance of decreasing the weight load on the combat soldier is paramount, this basis proves to be both realistic and practical.

The importance of tenacity in the ballistic resistance of needle-punched felts was noted early in the mathematical model obtained by Ehlers[2]. This empirical equation:

$$V = \log e^{4t} \sqrt{A_d W_i} \tag{1}$$

gave toughness, W_i, the same importance as areal density, A_d. Toughness is proportional to tenacity multiplied by elongation. The V in Equation (1) is the V_{50}, velocity in feet per second, and t is the thickness in inches. V_{50} is defined as the velocity at which 50 per cent of the missiles of a given geometry and weight will penetrate the target. It is calculated by averaging 10 shots in a velocity range of 125 ft/sec, five of which penetrate and five of which do not. The V_{50}'s reported were all obtained using a 17-grain (1.1 gm in the metric system), .22 caliber fragment simulator with ogive shaped geometry.

The toughness index, W_i, assumed a triangular stress-strain curve of PE/2 with P = tenacity and E = strain at break. The agreement of this equation with actual performance was quite good with regression existing under the "t" test at 95 per cent probability. It is interesting to note that a different least square regression line formula exists

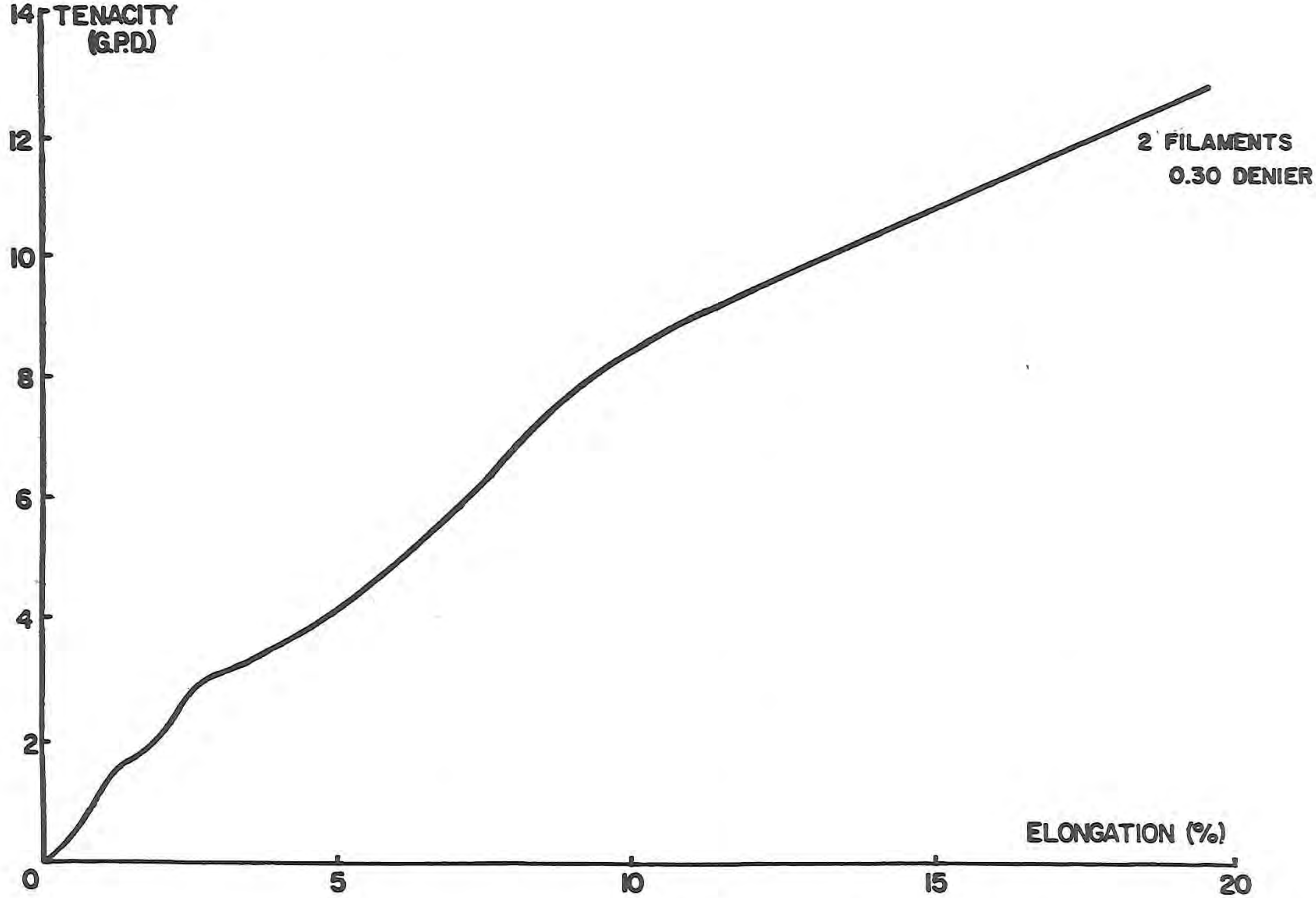

FIGURE 1. TYPICAL STRESS-STRAIN CURVE OF SPIDER SILK OBTAINED FROM NEPHILA CLAVIPES

for each fiber type, again confirming the importance of the first fiber parameter discussed. In Figure 2, the importance of tenacity is shown for both fabric and felt prepared from polypropylene fibers.

(4) Molecular Weight Distribution. The discussion of molecular weight distribution has been purposely separated from that of molecular weight, for although molecular weight is related to tenacity, the molecular weight distribution may be more readily related to the rheological properties of the polymer. For example, one might properly expect the low molecular weight fraction (tail) to respond more quickly to a deformation than the high molecular weight fraction. However, it is more likely that the presence of low molecular weight fractions leads to excessive crystallinity. It could be surmised that the narrowness of molecular weight distribution, at least in condensation polymers such as the polyamides, will lead to the best mechanical properties (high tenacity, high work to rupture). In any event, it is possible to alter the molecular weight distribution from the most probable state, where the weight average molecular weight is double the number average. The difficulty is in maintaining the polymer in a less probable state throughout the melting and spinning operations.

(5) Crystallinity. In the past, poorly characterized fibers have been used to prepare felts and fabrics, which were changed at will with little divulgence of these changes being made. The U. S. Army Natick Laboratories is now in the process of obtaining fibers which will be characterized not only by stress-strain properties but also by X-ray diffraction, light and electron microscopic techniques, and light scattering.

The melt spinning, drawing and heat setting operations obviously influence the crystallite size, orientation and perfection, but the effect of subsequent crimping, needling and hot-pressing operations (for reduction of the felt thickness) should not be overlooked. Samuels[7] has furnished a good model in utilizing eight techniques to characterize polypropylene fibers thoroughly. These techniques include wide-angle X-ray diffraction, birefringence, density, sonic modulus, dark field microscopy, small angle light scattering, tensile modulus, and small angle X-ray diffraction.

The use of nucleating agents to minimize the adverse effects of spherulite formation could be of benefit. Actually, the use of titanium dioxide as a delusterant has a side effect of reducing crystallite size because of its nucleating effect. Thus, the obvious experiment of comparing the efficiency of polyamide fibers with and without delusterant is indicated.

(6) Draw Ratio. Drawing a fiber orients the molecules, usually increasing the longitudinal strength and decreasing the lateral strength in a way favorable to resistance to catastrophic crack propagation. High tenacity polyamide fibers used in tire cord have a draw ratio in the range

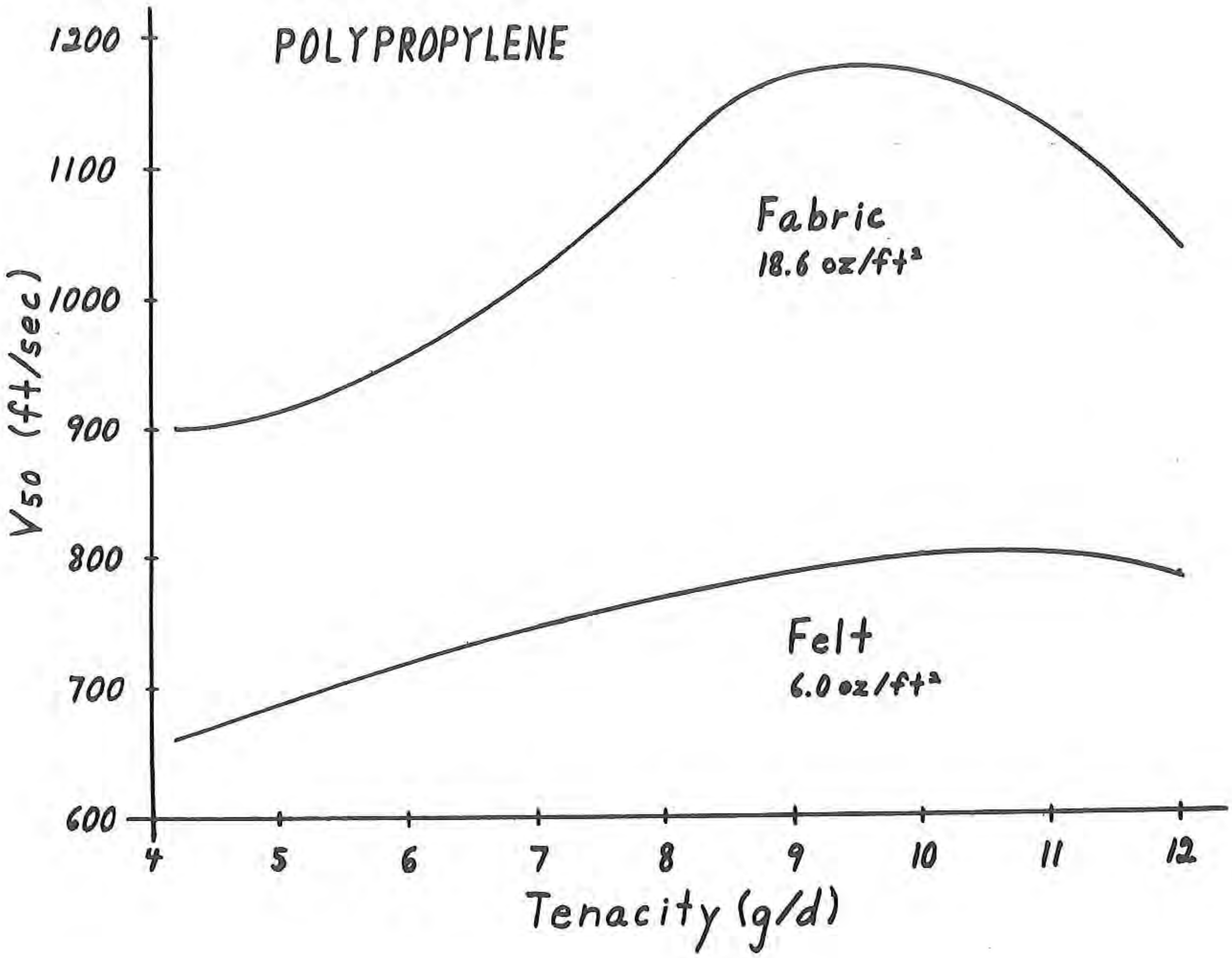

FIGURE 2. RELATIONSHIP OF V_{50} TO TENACITY OF POLYPROPYLENE YARN

of 4.9 - 5.2. Increasing this draw ratio further can increase the strength and modulus to only a small degree, partly because the draw ratio used in industry is nearly the maximum attainable for high-speed production of the specific polymer used. This draw ratio is only attained by using an 18-inch heated "heel" plate. The method of obtaining fibers with properties superior to those currently available will combine the use of high draw ratio with increased molecular weight.

The total orientation of a fiber actually results from the orientation introduced in the spinning operation as measured by the spin birefringence and from the additional orientation introduced by the subsequent drawing operation. A study has been conducted on the influence of draw ratio upon the mechanical properties of nylon 66[8]. The draw ratio was varied from 4.7 to 5.5 in increments of 0.2. Tenacity increased from 6.8 to 9.0 grams/denier as the draw ratio was increased. The elongation to break dropped from 22.3 percent at the lowest draw ratio to 15.6 percent at the highest level.

No felts were prepared in this study so that expressing a direct relationship between draw ratio and the ballistic properties of felts is not possible. The study is mentioned only to demonstrate the influence of draw ratio upon other parameters discussed in this paper.

(7) Elongation. The role that the elongation-to-break of the component fibers plays should be equivalent to that played by tenacity, according to the equation described in Section 2.a.(3). There are, however, some felt properties which negate any overemphasis upon the ultimate properties of the component fibers. If a natural felt of wool fibers with a high degree of compactness is broken in tension, considerable evidence of broken fibers is obtained. This is also true of felts containing a binder rather than depending upon needle-punching to maintain integrity. On the other hand, there is no evidence to indicate that fiber destruction is an important mechanism in felt breakage during ballistic impact. Even the stress-strain curve for felt gives us some indication of a different mechanism operating (Figure 3). The elongation to break for the felt is equal to or several times that of the component yarns. The mechanism is more likely a "stick-slip" variety rather than a stretching-to-break type. The term "stick-slip" is used to describe the phenomenon in which the fibers are stretched until the resulting force is great enough to overcome friction; the fiber slips and then sticks in a new position, and the entire process is repeated.

The stress-strength curves for felts at different rates of elongation can be nearly superimposed, as contrasted with the strong time-dependency that would be exhibited by the component fibers (Figure 4).

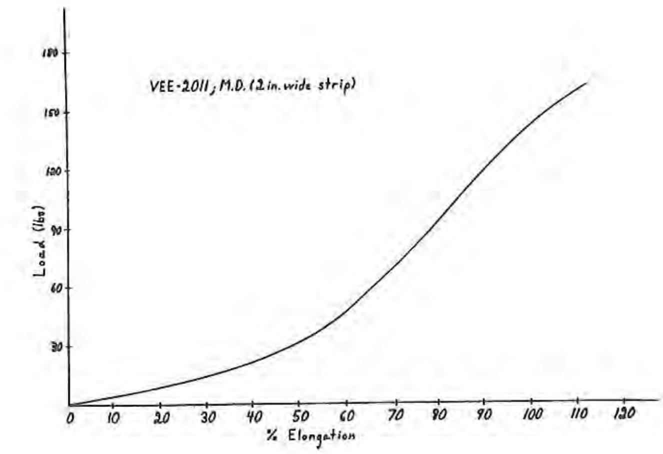

FIGURE 3. STRESS-STRAIN CURVE FOR A LIGHTLY NEEDLED FELT

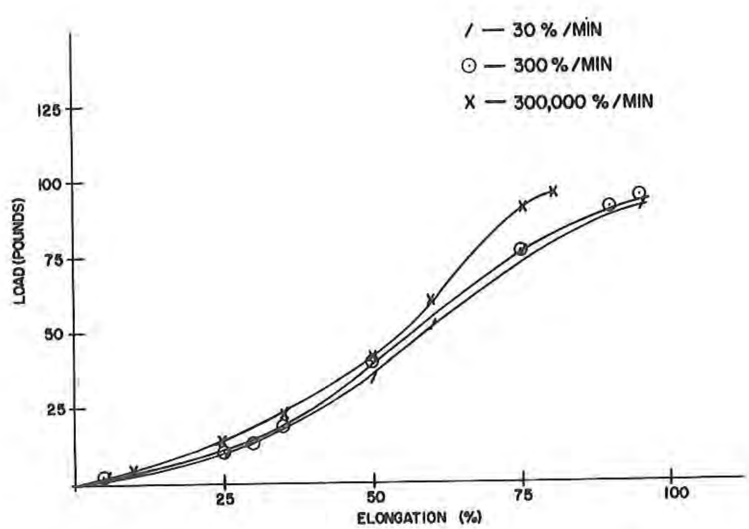

FIGURE 4. STRESS-STRAIN CURVES AT DIFFERENT RATES OF ELONGATION FOR NYLON FELT

(8) Work-to-Break. The work-to-break or "toughness" of a textile material is the area under the stress-strain curve under the conditions of test or interest. It is composed of the tenacity and elongation, which have been discussed previously. Work-to-break was the actual term used in the Ehlers formula, Equation (1). The obvious caution in considering this factor is that the fibers in a felt are not necessarily broken during ballistic impact.

An additional factor to be considered in optimizing work-to-break is the index advanced by Rosenthal where the tenacity multiplied by the square root of the elongation is a constant[9]. This would mean that increases in tenacity would be accompanied not only by decreases in elongation, but also by decreases in overall work-to-break.

(9) Fiber Surface. The mechanical testing of felts and yarns has indicated that needle-punched felts deform by a frictional "stick-slip" mechanism. As a minimum, the interaction between the individual fibers plays a predominant role in determining the mechanical properties of needle-punched felts. One could logically hope to improve the performance of a felt by using a simple lubricant (silicone) or abrasive (colloidal silica) to adjust the friction to the optimum degree. One also could consider applying a polymeric treatment to absorb the greatest quantity of energy possible during the impact. The absorption of energy during a ballistic impact is much more dependent upon response time than are the usual energy-absorbing demands posed by most commercial uses of materials.

McLoughlin[10] documented this problem quite well. Using data from Ferry[11], it can be seen how the mechanical loss (somewhat equivalent to the energy-absorbing ability) of methacrylate polymers varies with strain rate and temperature. For example, poly n-hexylmethacrylate has a loss peak at 1,500,000 cycles/sec at 125^{o}C but at 6 cycles/sec at room temperature. As the higher figure is more closely related to the strain rates of interest than the lower, it is seen that this polymer exhibits its best behavior at too high a temperature. As the glass transition temperature of poly n-hexylmethacrylate is about -5^{o}C, it appears that the high rate energy absorption, at least for this type of polymer, occurs at 100^{o}C above the glass transition and that the use of polymers with lower transition points is indicated.

Copolymers of 2-ethylhexyl acrylate and butyl methacrylate were prepared and solutions of these polymers used to treat felts. The felts were treated with add-ons of 2.5 and 5 percent and subjected to ballistic testing. The results are summarized in Table III.

TABLE III

INFLUENCE OF POLYMERIC TREATMENT UPON

BALLISTIC RESISTANCE OF THE STANDARD FELT

(54 oz/sq yd 1/3 in. thick Nylon Felt)

Copolymer	Add-On (%)	V_{50} (fps)	No.
50-50 2-ethylhexyl acrylate and butyl methacrylate	5.0	800	T76-66
50-50 2-ethylhexyl acrylate and butyl methacrylate	2.5	884	T562-66
30-70 2-ethylhexyl acrylate and butyl methacrylate	5.0	900	T103-66
30-70 2-ethylhexyl acrylate and butyl methacrylate	2.5	914	T102-66
Control - No Add-On	0.0	1059	T101-66

All the treatments resulted in a decreased ballistic performance. The static stress-strain properties were also altered, in some ways beneficially.

The tests were conducted on one-inch wide strips utilizing a constant rate of elongation of 12 in./min and a gage length of four inches. The results of these tests on a control felt and on treated felts are plotted in Figures 5 and 6.

The only encouraging note was that the copolymer with the greater quantity of acrylate (lower glass transition temperature) suffered the lesser ballistic impairment. If treatments of this type were to have

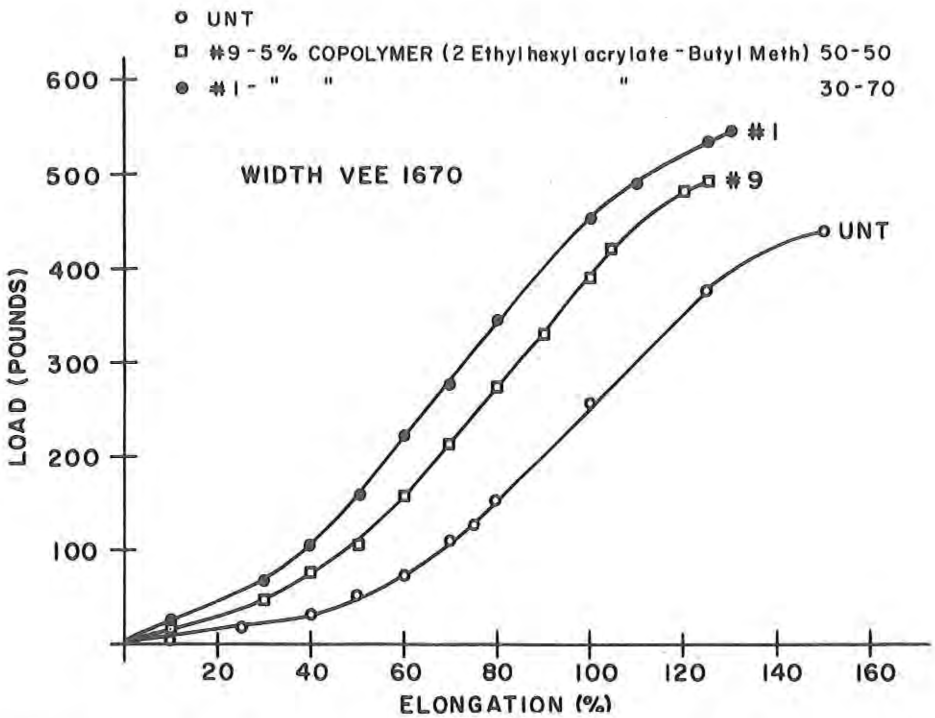

FIGURE 5. INFLUENCE OF POLYMERIC TREATMENT UPON FELT STRESS-STRAIN PROPERTIES (Width Direction)

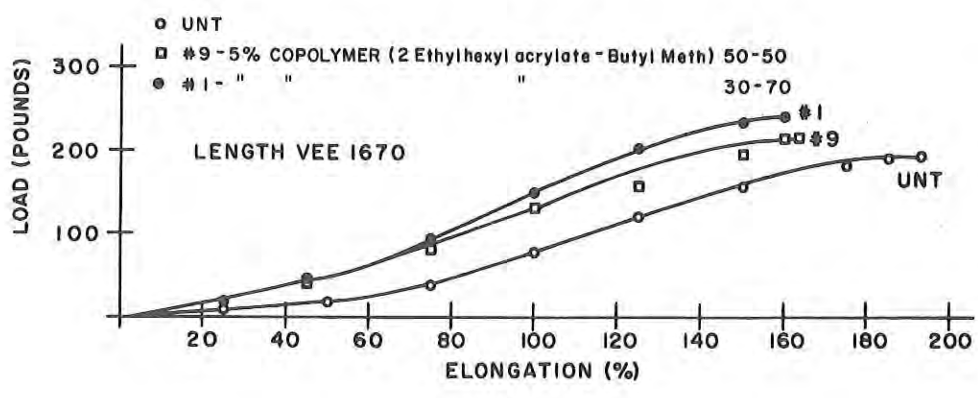

FIGURE 6. INFLUENCE OF POLYMERIC TREATMENT UPON FELT STRESS-STRAIN PROPERTIES (Length Direction)

any potential, the next logical step would be to treat the felts with polymers possessing extremely low glass transition temperatures. A series of silicones with molecular weights from 5,000 to 150,000 was used for this purpose with the rationale that the silicones all have effective glass transitions in the region of interest (less than -100^{o}C). The results of ballistic tests on these felts are given in Table IV.

TABLE IV

BALLISTIC RESULTS OF FELTS TREATED

WITH DIMETHYL SILICONE FLUIDS

Identification No.	Add-On (%)	Viscosity of Silicone	M.W. of Silicone	V_{50} (fps)
1.	10	50	5,000	864
2	10	264	12,000	877
3	5	1,015	25,000	911
4	10	1,015	25,000	888
5	15	1,015	25,000	871
6	10	10,270	57,000	746
7	10	28,600	80,000	779
8	10	100,000	100,000	---
9	10	1,058,000	150,000	811
Control	0	--	--	980

In summary, treatments utilizing polymers with low, intermediate, and high molecular weights and/or glass transition points have not improved the properties of felts. Any new approach to fiber surface should start with inspection of the polyamide fiber surface with the Scanning Electron Microscope in the original condition (Figure 7) and as altered by ballistic impact (Figure 8), and by use of surface treatments which can be chemically attached to the fibers in small amounts.

(10) Fiber Denier. The influence of fiber denier upon ballistic resistance is difficult to determine, both in felts and fabrics. From a practical standpoint, it has been impossible in the past to obtain fibers differing in denier but possessing similar ultimate mechanical properties as shown by the stress-strain curves. A specific attempt was made in the past to study the influence of fiber denier upon the ballistic properties of fabrics using Nylon 6,6 of 3, 6 and 15 denier. Superior results were obtained with the six denier fiber, but differences in the mechanical properties of the different fibers made it impossible to isolate denier as a single measurable parameter.

In felts, work has been conducted to determine the optimum denier of acrylic fibers. These were extremely low density felts used for their buoyancy as well as their ballistic properties. Figure 9 shows the influence of denier of a modacrylic staple fiber upon the ballistic resistance of resultant felt batting[4]. The use of small denier fibers would be indicated in this case.

b. Fabrication Parameters

(1) Type of Needling. A limited study of the effect of needle type upon ballistic resistant properties was recently concluded[12]. The results of this study are shown in Table V.

TABLE V

EFFECTS OF NEEDLE TYPES ON BALLISTIC FELTS

Felt Style	Needle Type	Areal Density (oz/sq yd)	V_{50} (fps)	Normalized
48-04-1	TMW-3	6.56	1051	1037
48-04-2	TMW-7	7.06	1126	1098
48-07	Torrington	7.22	1088	1057
48-08	TMW-5	6.60	1070	1062

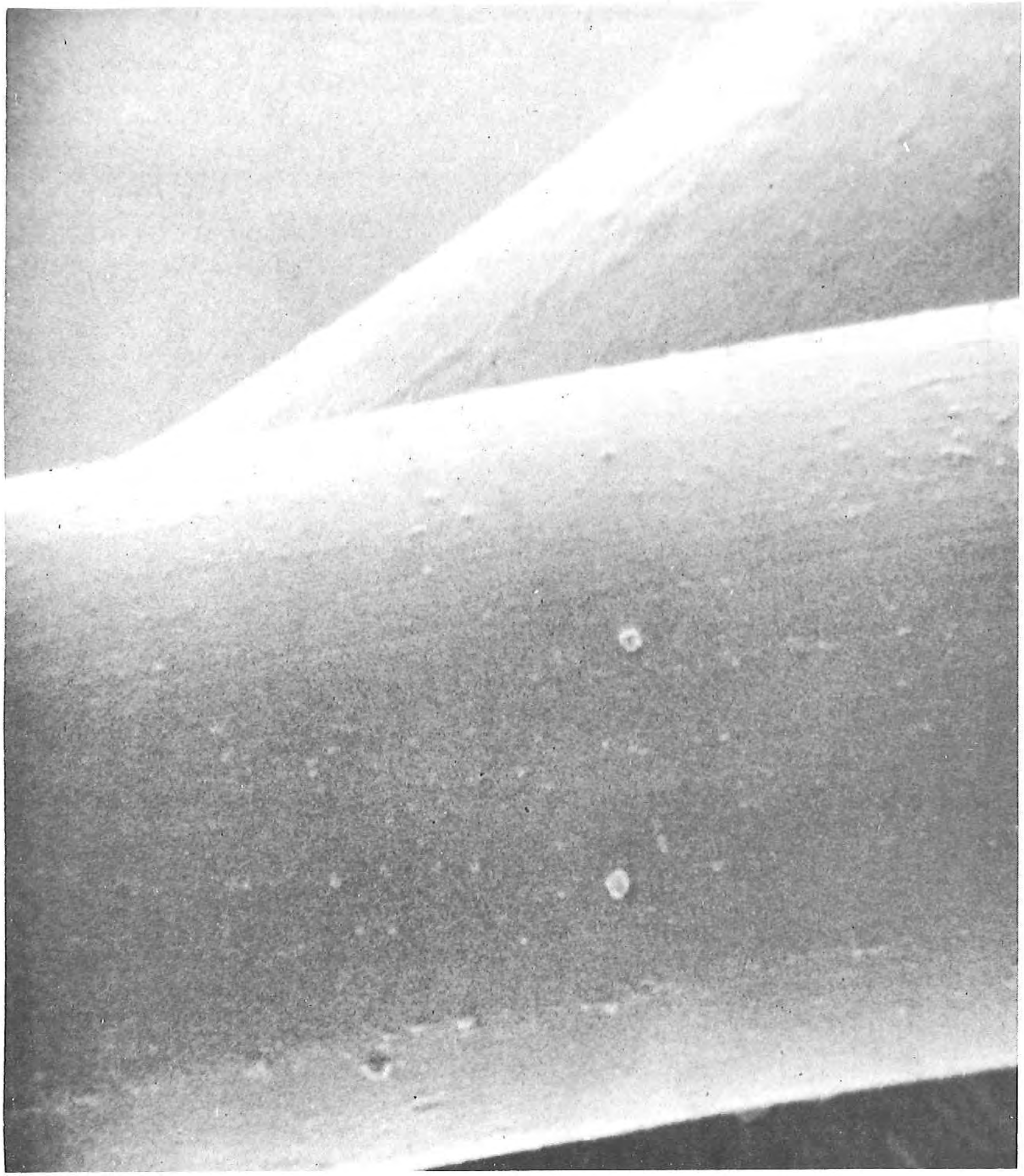

FIGURE 7. SCANNING MICROGRAPH OF NYLON 66 FIBER (4114X)

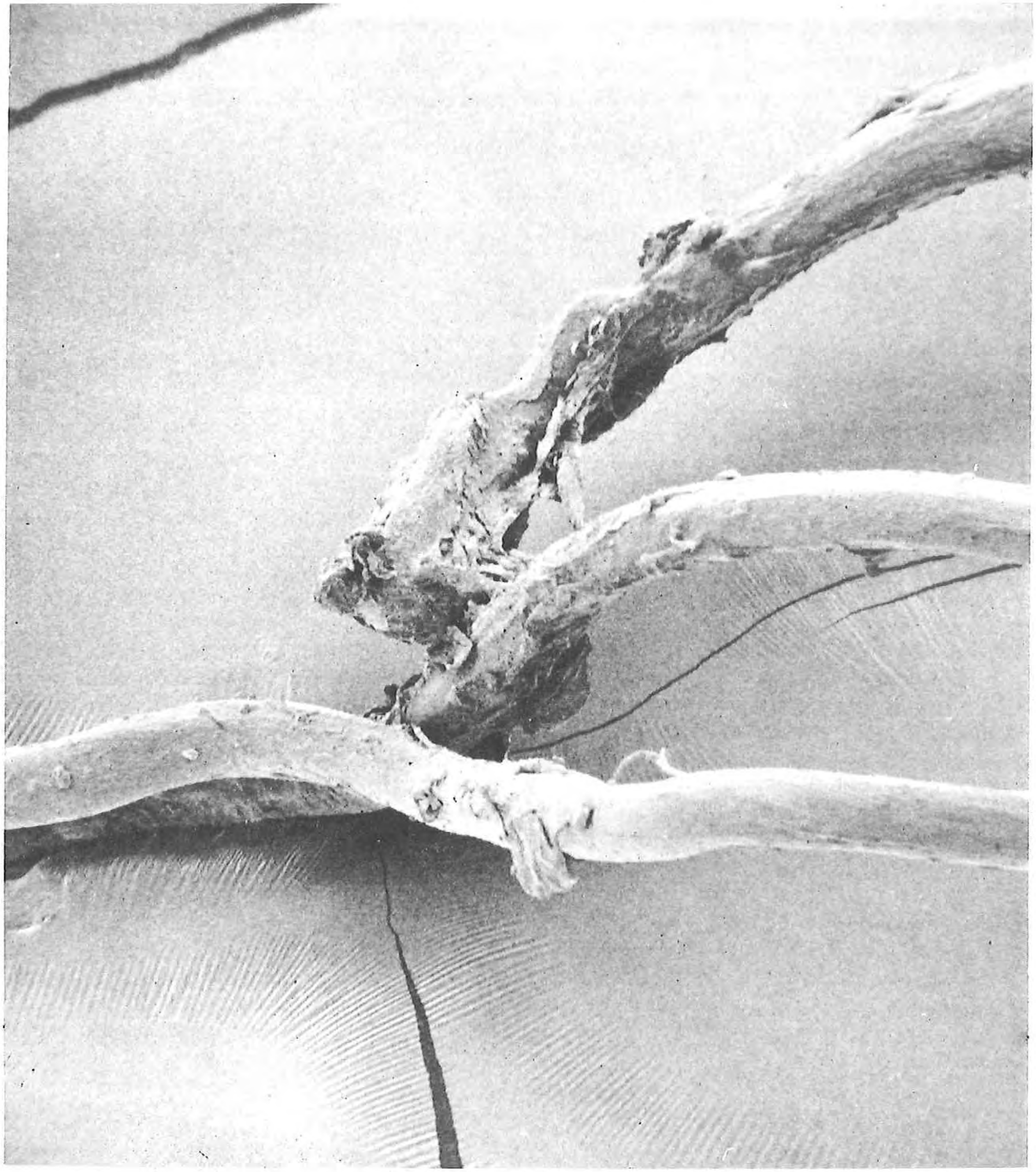

FIGURE 8. SCANNING MICROGRAPH OF NYLON 66 FIBER AFTER BALLISTIC IMPACT (420X)

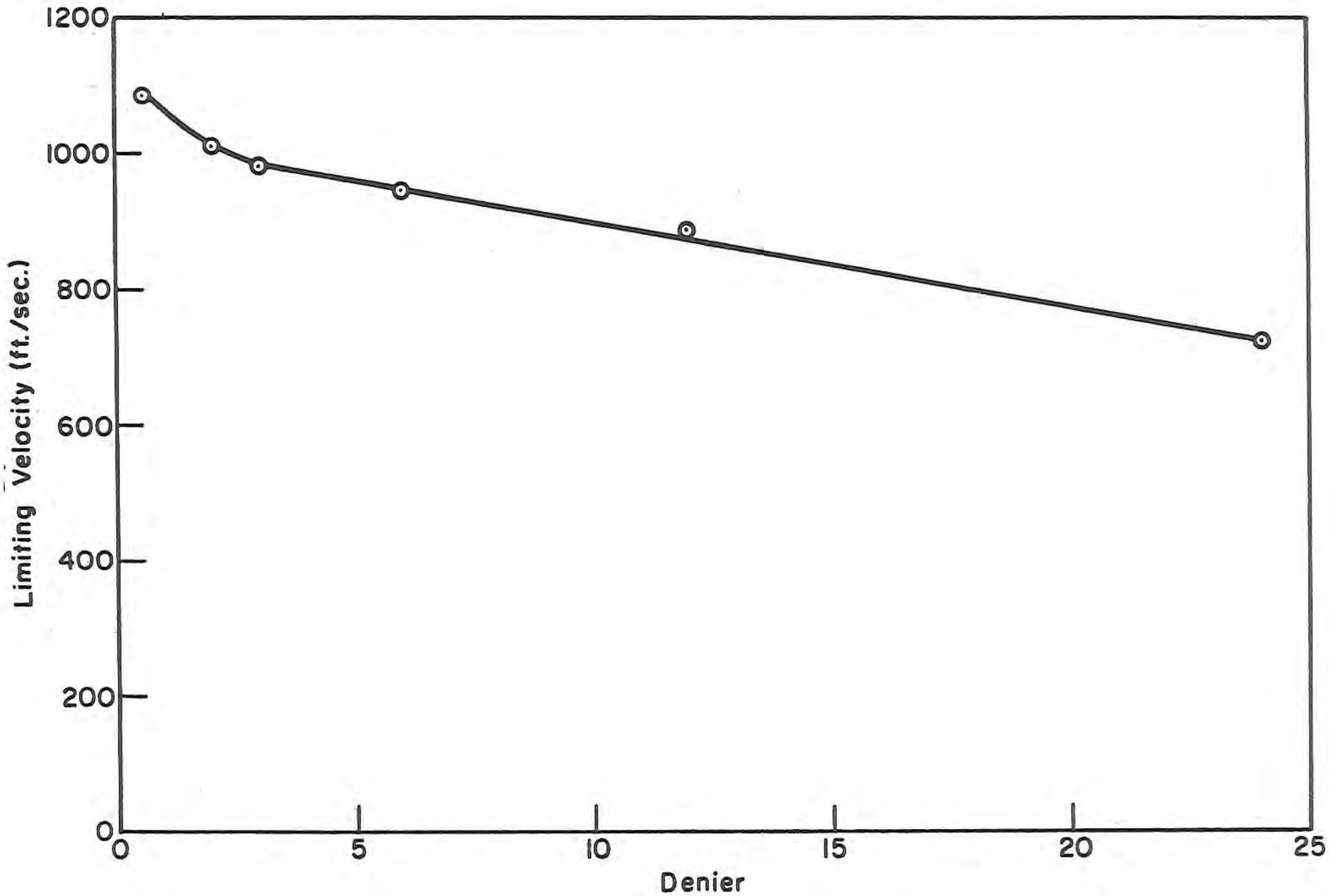

FIGURE 9. EFFECT OF FIBER DIAMETER UPON BALLISTIC PERFORMANCE

MODACRYLIC Staple Fiber (2" - 3" cut)

The TMW needles are all special needles* which differ in efficiency, i.e., fiber-carrying capacity. TMW3 has a throat depth of 0.002-inch and a pickup of 0.001-inch. TMW5 has a throat depth of 0.004-inch and a pickup of 0.001-inch. TMW7 has a throat depth of 0.005-inch and a pickup of 0.002-inch. All the TMW needles have three close barbs, one per side.

The major conclusion is that the type of needle used is not an important parameter. This is not to say that improper selection of needles could not result in inferior felts, but rather that variations in needle type by a manufacturer skilled in the art will produce little variation.

(2) Density of Needling. By examining the mechanical properties of felts at slow speeds, high speeds and while under impact, several points are clarified. The first is that the process is dependent upon fiber-fiber interaction, rather than breakage, to a very large degree, and that anything that interferes with this interaction (treatments, binders, reinforcing fabrics)tends to lower the ballistic resistance. Secondly, the slow speed of the reaction of the felt to impact by a missile can be determined by high-speed photographs (Figures 10 and 11). These figures show typical silhouette photographs of felt impacted with the 17-grain fragment simulator. These photographs are of the same missile impact with a time separation of 77 microseconds. From such photographs, it is possible to determine the speed with which the material reacts to gross deformation to the impact. This deformation can be designated as a "kink" wave velocity, which is the north-south direction in the figures shown.

In Figure 12, kink position versus time after impact has been plotted for numerous tests on nylon ballistic fabric and on nylon needle-punched felt. The above statement of the slowness of felt to react to the impact becomes apparent from Figure 12, especially as compared to the faster reaction time exhibited by the nylon fabric. Because of this fact, a felt's ability to absorb the energy of a missile (as compared, for example, to that of a fabric) is strongly dependent upon the relatively high elongations attained even during ballistic impact.

Finally, all previous work intended to investigate the influence of needling was in the range of many hundreds of penetrations per inch and, in fact, showed little effect of needling. Of all the parameters that could be selected (angle of needling, type of needling, angle of ply, fiber length) it may seem strange that the amount of needling was given primary emphasis. However, the importance of fiber mobility (fiber-fiber interaction) for effective performance made this direction

*Made for Fiberwoven Corporation, Elkin, North Carolina by the Textile Machine Works, Reading, Pa.

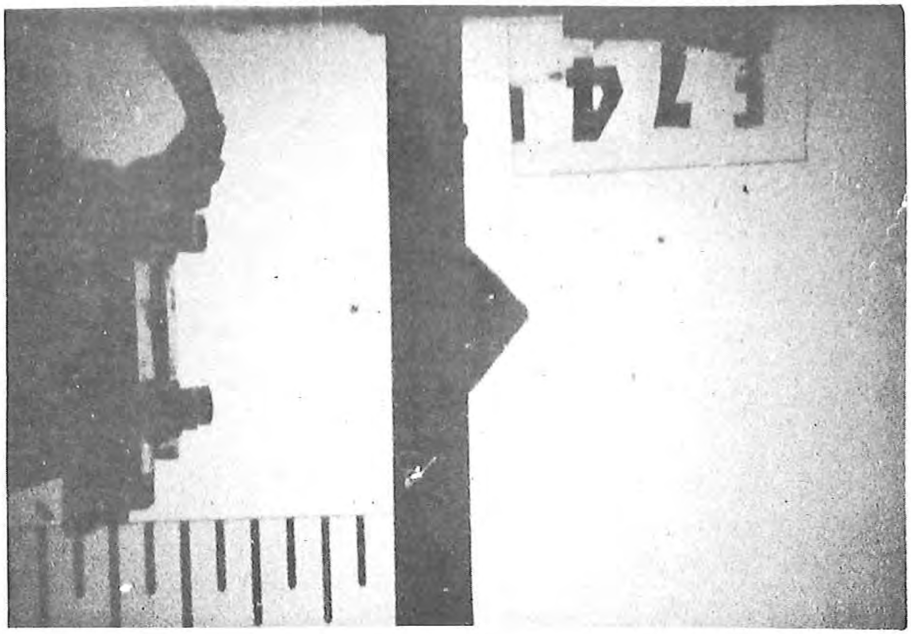

FIGURE 10. FELT DEFORMATION INDUCED BY IMPACT WITH 17-GRAIN FRAGMENT SIMULATOR

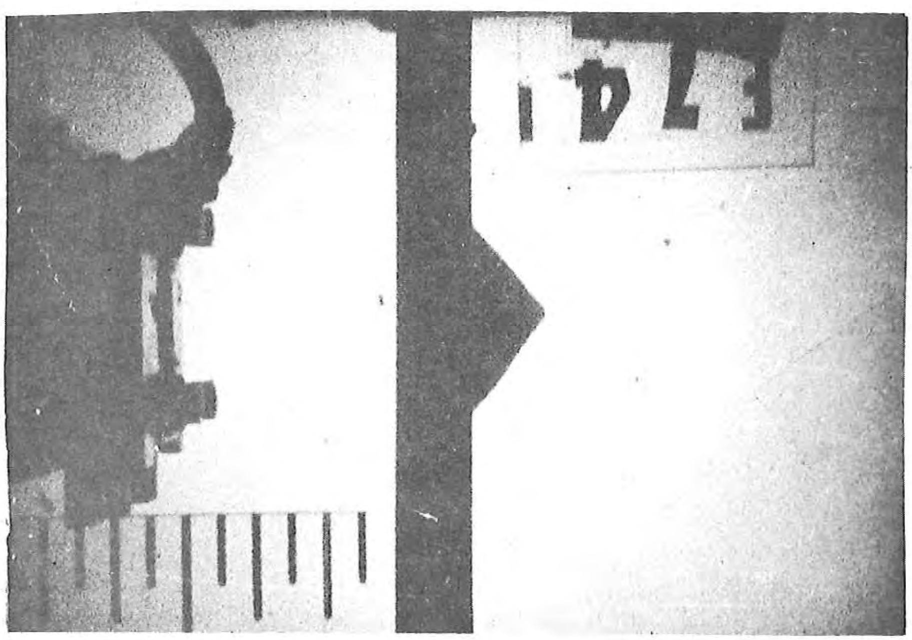

FIGURE 11. FELT DEFORMATION 77 MICROSECONDS AFTER FIGURE 10

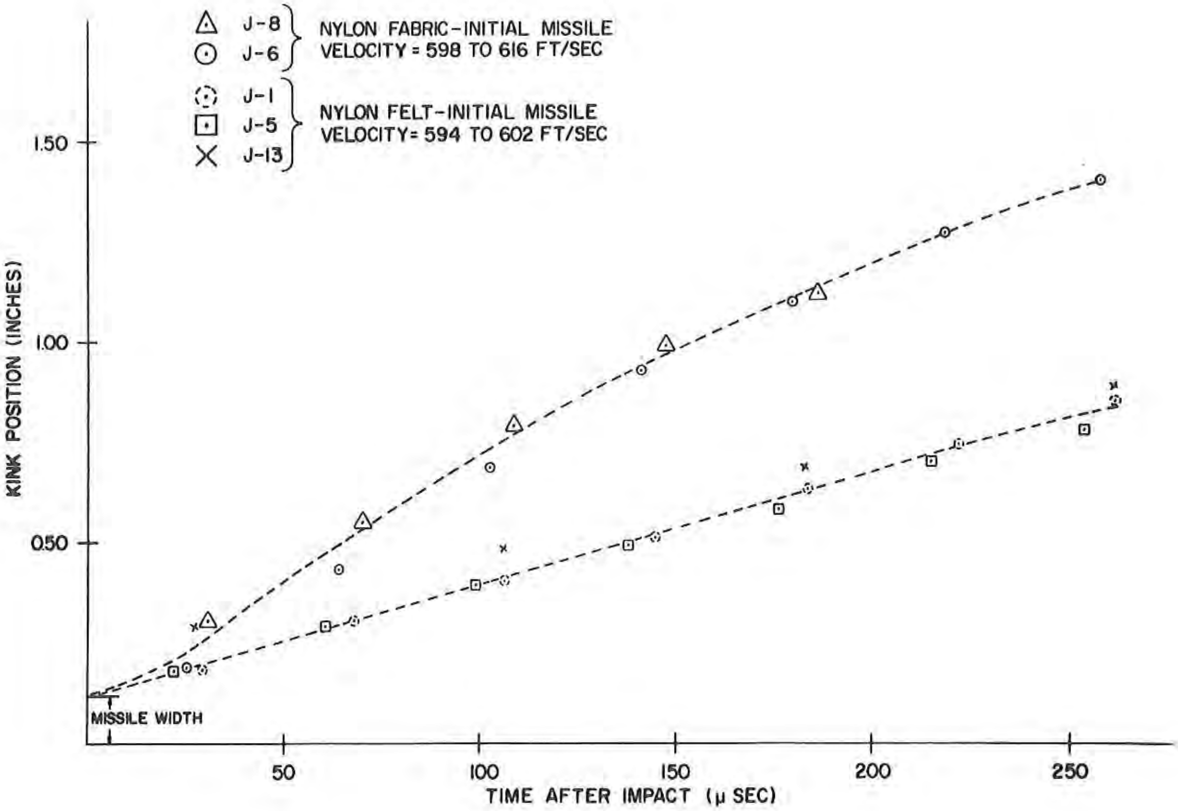

FIGURE 12. COMPARATIVE KINK POSITION OF NYLON FABRIC AND NYLON FELT AT EQUAL IMPACT VELOCITIES

more logical. From these studies, it was concluded that previous work and most industrial applications and "know-how" had led to over-needling of a complete order of magnitude. A new study of needling started with only 277 penetrations per inch and added additional needlings. The results of this study are illustrated in Figure 13. The materials designated as A. (VEE 2011), O. (VEE 2012), B. (VEE 2013), and C. (VEE 2014) were prepared as designated in the following paragraphs(13):

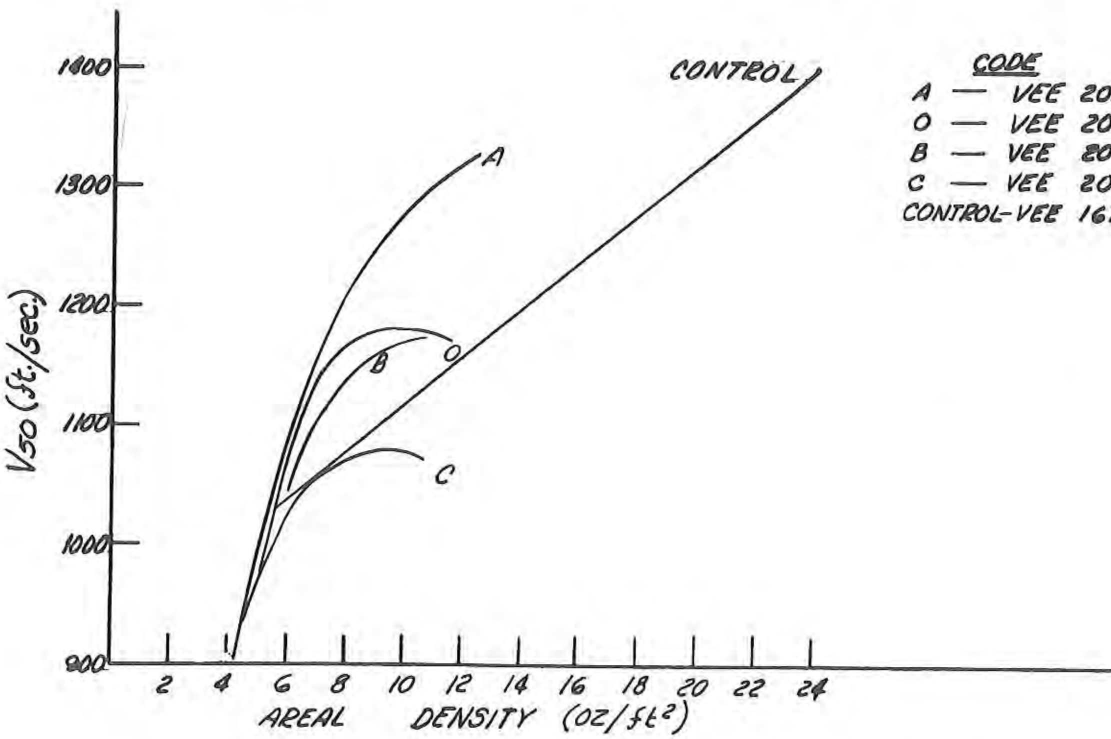

FIGURE 13. V_{50} AS A FUNCTION OF AREAL DENSITY FOR FELTS WITH DIFFERENT DEGREES OF NEEDLING

(a) A - VEE 2011

This needle-punched felt was prepared from 67 per cent, 6-denier, 3-inch staple uncrimped nylon, and 33 per cent, 3-denier, 2-1/2-inch staple crimped nylon. The 4-ounce batts resulting from the carding operation were needled (277 penetrations per square inch) and cross-lapped at about 20^{o}. Four batts were needled together (277 penetrations per square inch) to give a felt with a thickness of 0.110 to 0.125-inch and a weight of 13.3 ounces per square yard.

(b) O - VEE 2012

This felt was produced by taking Felt VEE 2011, which had 277 needlings per square inch, and needling the opposite surface an additional 277 penetrations per square inch. The resulting weight was 11.8 oz/sq yd and the thickness equal to 1.090 to 0.095 inches. The 277 penetrations per inch used on the original 4-ounce/sq yd batts are generally ignored, since they are common to all the felts, used only for furnishing integrity to them, and neither add nor detract from the ballistic performance.

(c) B - VEE 2013

VEE 2012 was given two additional needlings of 277 penetrations per square inch -- one on each side. This felt with a total of 1108 penetrations per square inch has a weight of 11.7 oz/sq yd and a thickness of 0.085 to 0.095-inches.

(d) C - VEE 2014

This felt was produced by doubling VEE 2012 and needling once on each side. The resulting felt had a weight of 25.4 oz/sq yd and a thickness of 0.135 to 0.150-inches.

From these studies it was concluded that the optimum needling for ballistic purposes is the single needling of 277 penetrations per inch[9].

The curve of ballistic resistance (as shown by V_{50}) versus areal density is of a different form for the lightly needled felt. The more heavily needled felts lose their advantage over other materials (i.e., fabric, the regulation 1/3 inch felt) at much lower areal densities.

A comparison between the lightly needled felt for various numbers of layers, the regulation nylon fabric, and the heavy 50 oz/sq yd highly needled standard felt is given in Figure 14.

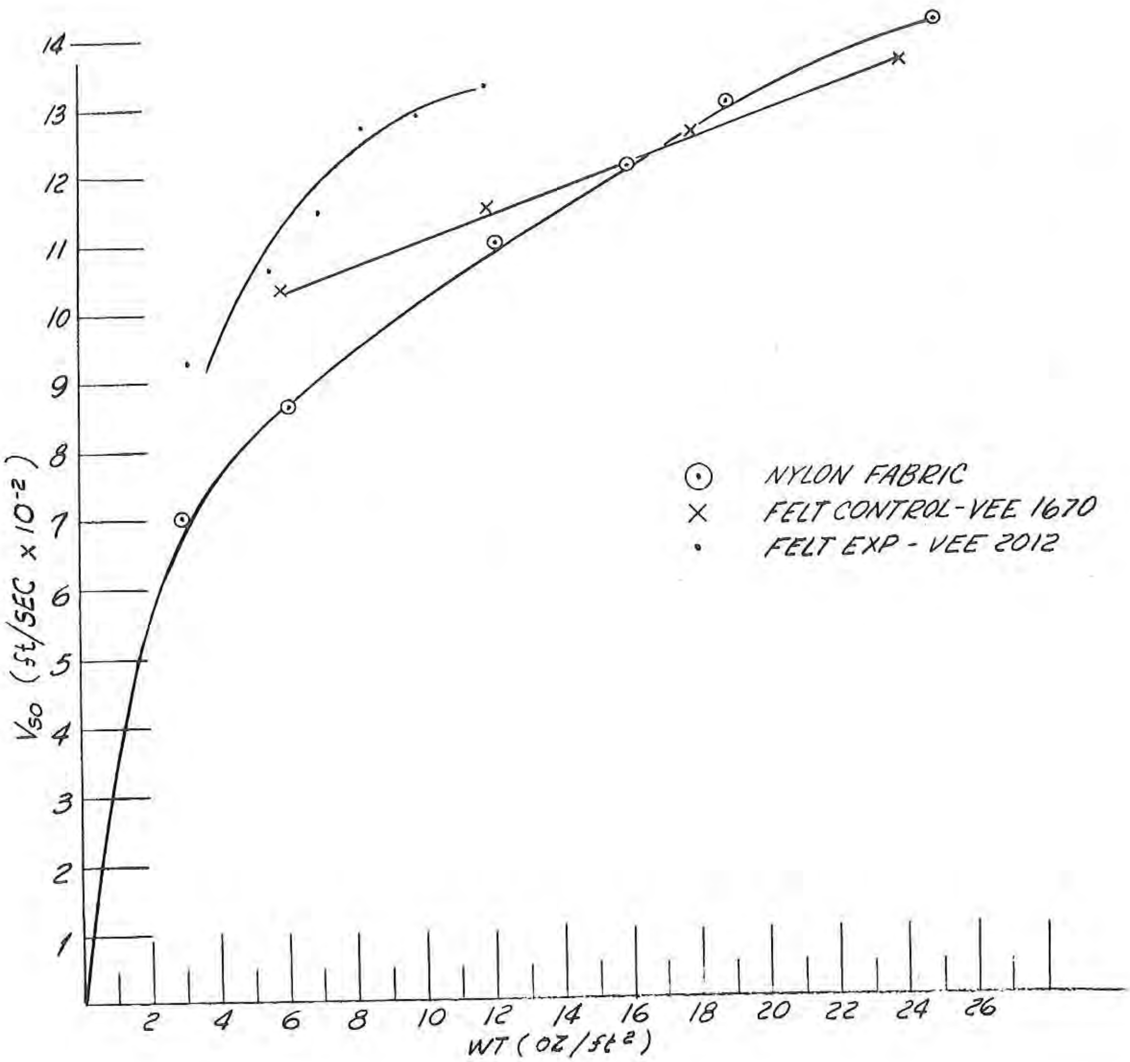

FIGURE 14. COMPARISON OF BALLISTIC PROPERTIES OF THE BEST EXPERIMENTAL FELT WITH FABRIC AND STANDARD FELT

(3) Angle of Needling. Techniques are available which allow a felt to be needled at different angles. One would expect that great differences in felt properties would occur, depending upon the average direction of the fibers introduced by needling. A photomicrograph of a needled felt shows the influence of needling in forcing some fibers to assume the through thickness direction (Figure 15).

The preliminary results of needling studies are shown in Table VI.

These initial studies indicate that angle of needling is in fact a rather minor parameter compared to the previous factor, amount of needling. This conclusion applies whether crimped or uncrimped fibers are used. It should be emphasized that these studies are still in a preliminary stage and it is possible that it is not yet known how to obtain the greatest benefit ballistically from angle of needling.

(4) Crimped versus Uncrimped Fibers. The use of crimped and uncrimped fibers in various proportions has been the subject of several studies. Results of the latest study are shown in Table VI.

TABLE VI

FELT, CRIMPED AND CRIMPED/UNCRIMPED

Style No.	Description	Angle of Needling (Degrees)	Areal Density (oz/sq yd)	V_{50} (fps)	Normalized* (fps)
48-10	Nylon, Crimped	12	5.33	1125	1142
48-11	Nylon, Crimped	8	5.21	1124	1144
48-12	Nylon, Crimped	20	5.35	1152	1168
48-15	Nylon, Crimped	0	5.13	1123	1145
48-09	65/35 Uncrimped/ Crimped Nylon	0	4.91	966	993
48-13	65/35 Uncrimped/ Crimped Nylon	8	7.11	984	956
48-14	65/35 Uncrimped/ Crimped Nylon	12	5.55	954	966
48-17	65/35 Uncrimped/ Crimped Nylon	20	6.27	994	988

*Normalized Range, Crimped Nylon 1142-1168

Normalized Range, 65/35 Uncrimped/Crimped 956-993

FIGURE 15. PHOTOMICROGRAPH OF NEEDLE-PUNCHED FELT (100X)

An attempt was made to keep all factors except the use of crimped and uncrimped fibers constant. Angle of needling was altered in some cases, but even here each sample has a counterpart with the same angle of needling and only the amount of uncrimped fiber changed. The conclusion to be drawn from these data is the superiority of the felts prepared from crimped fibers. The use of crimped and uncrimped fibers is still the subject of intense investigations, since unpublished work done at Natick Labs has shown that careful laboratory preparation of a felt from 100% uncrimped fiber can give ballistic results superior to any of those shown in Table VI. This apparent anomaly is due to the three factors involved in comparing uncrimped and crimped fibers. The first of these factors is that uncrimped fiber generally has higher strength than the crimped fiber. The second factor is that uncrimped fiber has an opportunity for greater fiber-to-fiber contact than the ~~un~~crimped fiber. The last factor concerns the extra entanglement which may occur with crimped fibers.

(5) Length of Fibers. In general, ballistic resistance rises with the length of staple fiber used. The rise is rapid in the very early stages from one to four inches and very moderate thereafter. It is more and more difficult to process a felt as the length of fiber is increased beyond four inches; therefore, this area of very long fibers has not been suitably investigated. An infinite fiber length can also be produced by an entirely different, new method of processing, known only to a few industrial concerns.

(6) Thickness of Felt. The thickness of the felt for a given weight is one of the most important parameters in determining its ballistic resistance. In general, the thicker the felt, the higher the ballistic resistance. For the clothing designer, the thinner the felt, the easier it is to incorporate into the clothing system. For this reason, the attempt is made to lower the thickness of the felt to a reasonable level with the least loss possible in ballistic performance. The worst way to lower the thickness is by needling. The best method is to press the felt at the lowest temperature possible. Examples are given in Table VII.

TABLE VII

EFFECT OF THICKNESS UPON THE BALLISTIC RESISTANCE

OF NEEDLE-PUNCHED FELTS

Sample	t(indiv layer-in.)	t(total-in.)	Areal Density (oz/sq ft)	V_{50}(fps)
Felters Nylon #5U	.332	1.33	8.8	1491
Felters Nylon #5P_1	.155	.62	8.8	1388
Felters Nylon #5P_2	.133	.80	8.6	1209
Felters 1.1	.520	.520	6.0	1118
Felters 1.2	.330	.330	5.6	1069

The results show that the first felt #5U lost over 100 fps when properly pressed from 0.332-inch to 0.155-inch and fired as a four-layer structure of 8.8 oz/sq ft. The third felt listed was prepared from the same felt, #5U, but the pressing procedure so altered the structure that five layers were needed to obtain the same areal density. Needling could have been used to attain the decreased thickness, but the loss would have been even more severe as shown in Section 2.b.(2), Density of Needling. The last two felts listed show the effect of pressing upon the ballistic resistance of a one-layer felt. The loss was quite moderate but the thickness change was also more moderate than in the previous example.

(7) Angle of Ply. The apex angle is the angle made by the web in the cross lapper as it is formed into a batting. The web is a very thin film of fibers (approximately one to four oz/sq yd) leaving the card or Garnet machine. This apex angle is usually about 28° in all or 14° as measured from the perpendicular. Small changes in the apex angle apparently cause very little change in the ultimate ballistic properties of the felt.

c. Dynamics of Felt Impact

The dynamic properties of needle-punched felts have been investigated in some depth. One method used tensile testing of felt strips at different rates of straining. Rates of 30%/min and 300%/min were attainable using an Instron tester, and a pneumatic type tester was used to obtain a straining rate of 300,000%/minute. The results of these tests have been discussed briefly and shown previously (Figure 4). The important feature is the almost complete lack of time dependence exhibited. This was one of the pieces of evidence which led to the concept of a "stick-slip" mechanism rather than the usual fiber breakage mechanism characteristic of fabrics.

Additional evidence for this mechanism from the same study was given by the characteristic elongation of the felt (80 to 100 per cent), or four or five times that expected from extension of the fibers alone.

A second method of studying the dynamic properties of felt involved the use of a high-speed compression penetration test. This test utilized a penetration probe with a point shaped like the 17-grain fragment simulator used for ballistic evaluation and a test speed of 10,000 inches per minute[1]. The test results for various felts correlated quite well with the missile energies calculated from the V_{50} results (Figure 16).

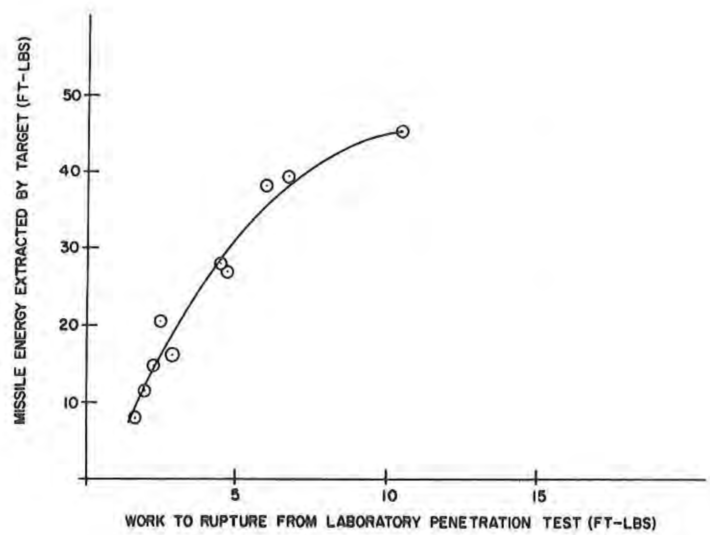

FIGURE 16. RELATIONSHIP BETWEEN WORK-TO-RUPTURE BY COMPRESSION PENETRATION TESTS AND V_{50} BY BALLISTIC FIRING

The third method used to investigate the dynamic properties of felt involved the actual impact of the felt with a missile fragment. High-speed photography was used to follow the interaction (Figure 17).

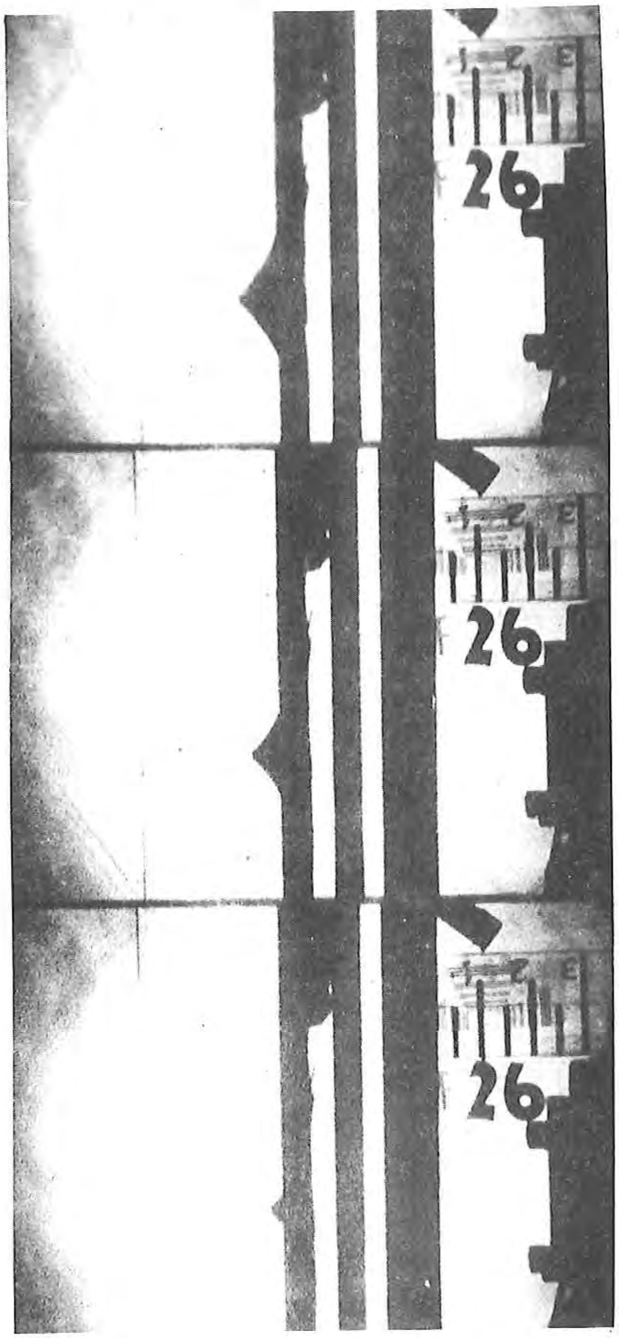

FIGURE 17. SEQUENCE PHOTOGRAPHS OF MISSILE-FELT INTERACTION

The 17-grain fragment simulator moves from right to left with each frame, stopping the action 77 microseconds after the frame directly above it. The Dynafax high-speed camera was actually capable of speeds equivalent to 38 microseconds/frame, but only alternate frames are shown in this strip[14].

Because a silhouette method was used, there is a tacit assumption that the deformation is homogeneous within the cone and that the velocity of all the felt material within the cone is the same. Based upon this assumption, information concerning the amount of material in the cone and its velocity can be obtained. The results of such studies for both felt and nylon ballistic fabric at the same impact velocity (500 fps) are described in Figure 18. Figure 18, obtained by a simple kinetic energy calculation, shows that the fabric picks up kinetic energy from the missile much faster than the felt. (This was one of the facts leading to the development of a lightly needled felt with more mobility.)[15] The data from the high-speed photographs of the missile-felt interaction can be reduced to give projectile displacement information (Figure 19).

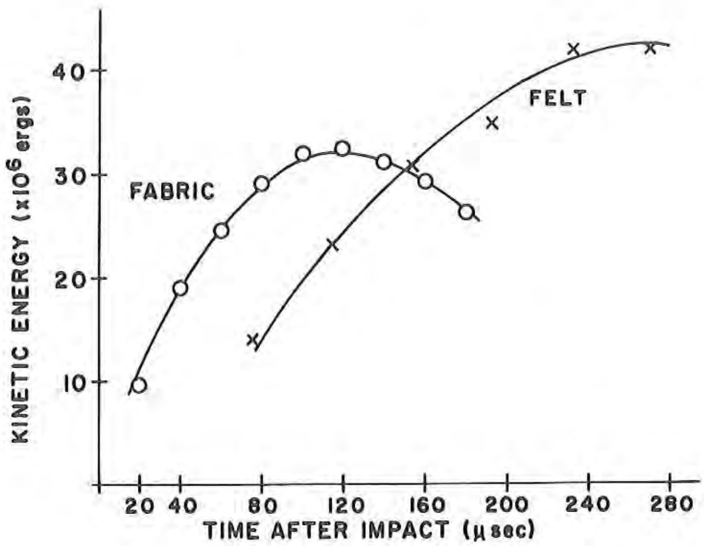

FIGURE 18. KINETIC ENERGY OF MOVING TARGET WITHIN THE CONE

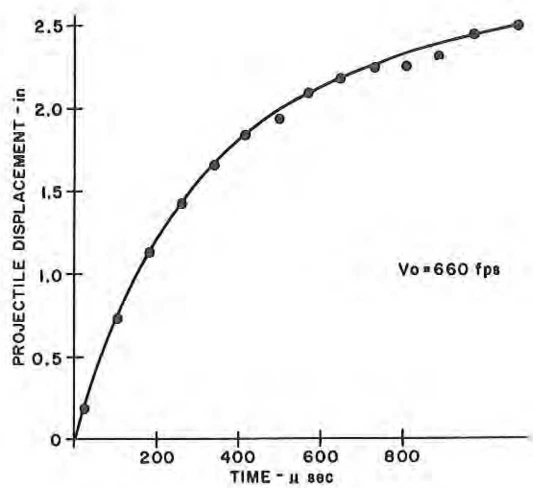

FIGURE 19. PROJECTILE DISPLACEMENT VERSUS TIME CURVE

These data can, in turn, be differentiated graphically to yield a velocity-time plot (Figure 20). A second derivative gives a deceleration-time profile which is simply converted into a force-time plot (Figure 21).

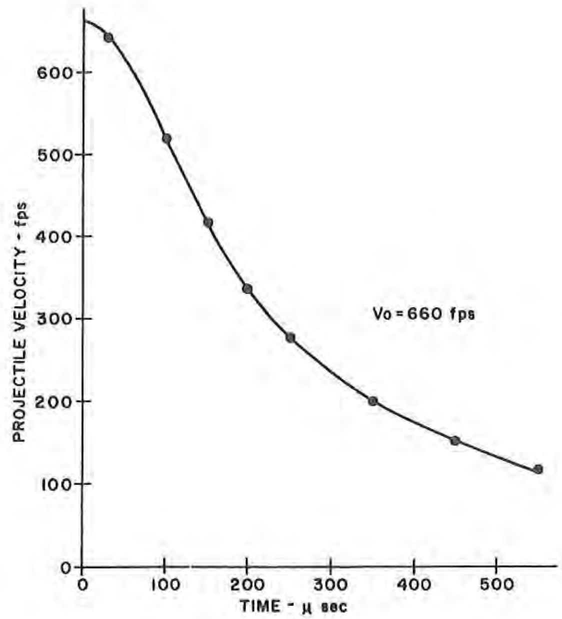

FIGURE 20. PROJECTILE VELOCITY VERSUS TIME CURVE

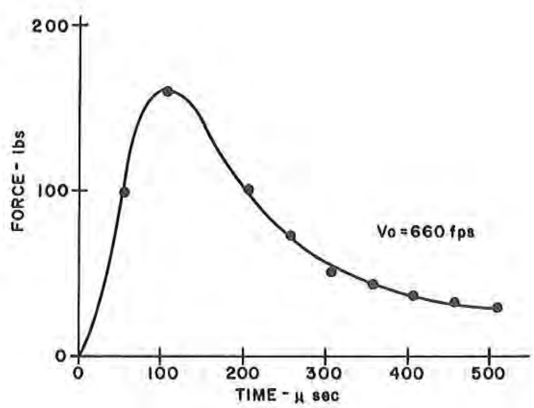

FIGURE 21. FORCE VERSUS TIME CURVE

Another method was available for determining the response speed of a material like felt, using the Henry Morgan KLH Sound Velocity Measuring Device. The results of some of the studies conducted are shown in Figure 22.

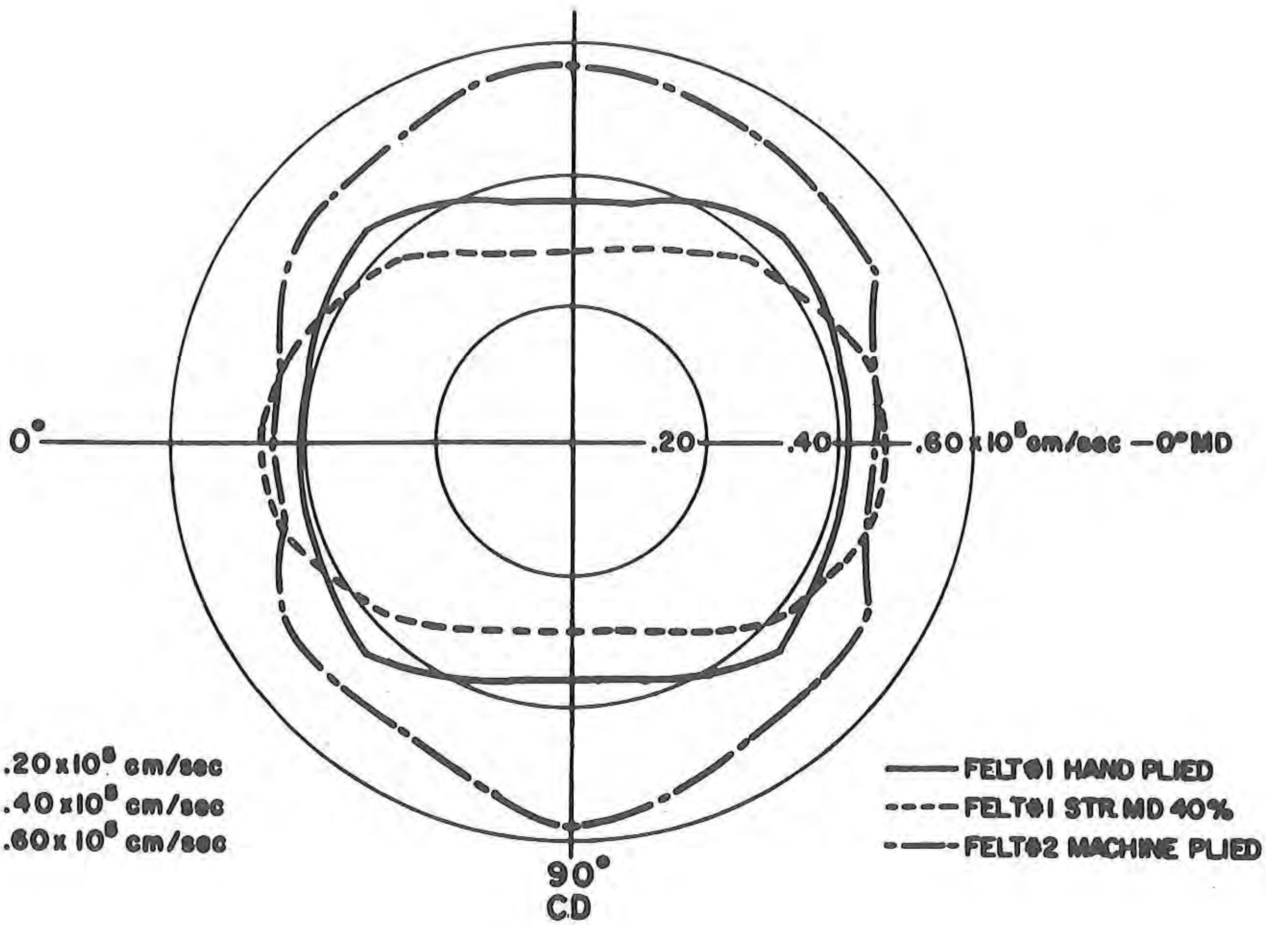

FIGURE 22. VELOCITY OF SOUND IN NYLON FELT AS A FUNCTION OF ORIENTATION

The conclusions most easily obtained from Figure 22 are as follows: (1) Considering the method of manufacture, the felt is rather isotropic; (2) Stretching the felt in the machine direction increased the sound velocity in that direction, as would be expected; and (3) the velocities are rather low: 0.5×10^5 cm/sec or 1500 fps as contrasted with a velocity of 8500 fps expected for the component fibers.

Most of the preceding studies were deficient in assuming homogeneous deformation within the cone of deformation. To determine displacement-time data for many points on the felt specimen simultaneously, it was necessary to utilize a new technique entitled "The Spark Gap Technique."(16) In this method, the points are located and defined as spark gaps on the rear of the felt specimen to be impacted. These spark gaps are obtained by sewing fine wires into the felt at 1/2-inch intervals (Figure 23). The wire between the spark gaps is not taut to protect the experiments from adverse interactions during impact. During the impact by a .22 caliber fragment from a Hornet rifle, the felt specimen was held in a four-inch diameter circular opening. A switch was placed in the path of the missile (on the front of the felt surface) to trigger the electrical pulse from the pulse generator. Thus, a 10,000-volt pulse traveled to the back of the felt via the wire to the spark gaps. These pulses were of 2 microseconds duration and occurred 86 microseconds apart. Pinpoints of light at the spark gaps defined the location of each station every 86 microseconds. These pinpoints of light exposed a film and produced results typically like those shown in Figure 24. The data were then plotted to show the position-time relationship during the impact event for the stations on the rear surface of the felt. The following conclusions can be realized from this work:

(1) The felt is deformed in different amounts within the cone dependent upon the distance from the impact.

(2) Force-time curves can be obtained by double differentiation of the position-time data. This information could be valuable for predicting the dynamic properties of the felts and for improving the felt system. The difficulty is the large error inherent in double differentiation.

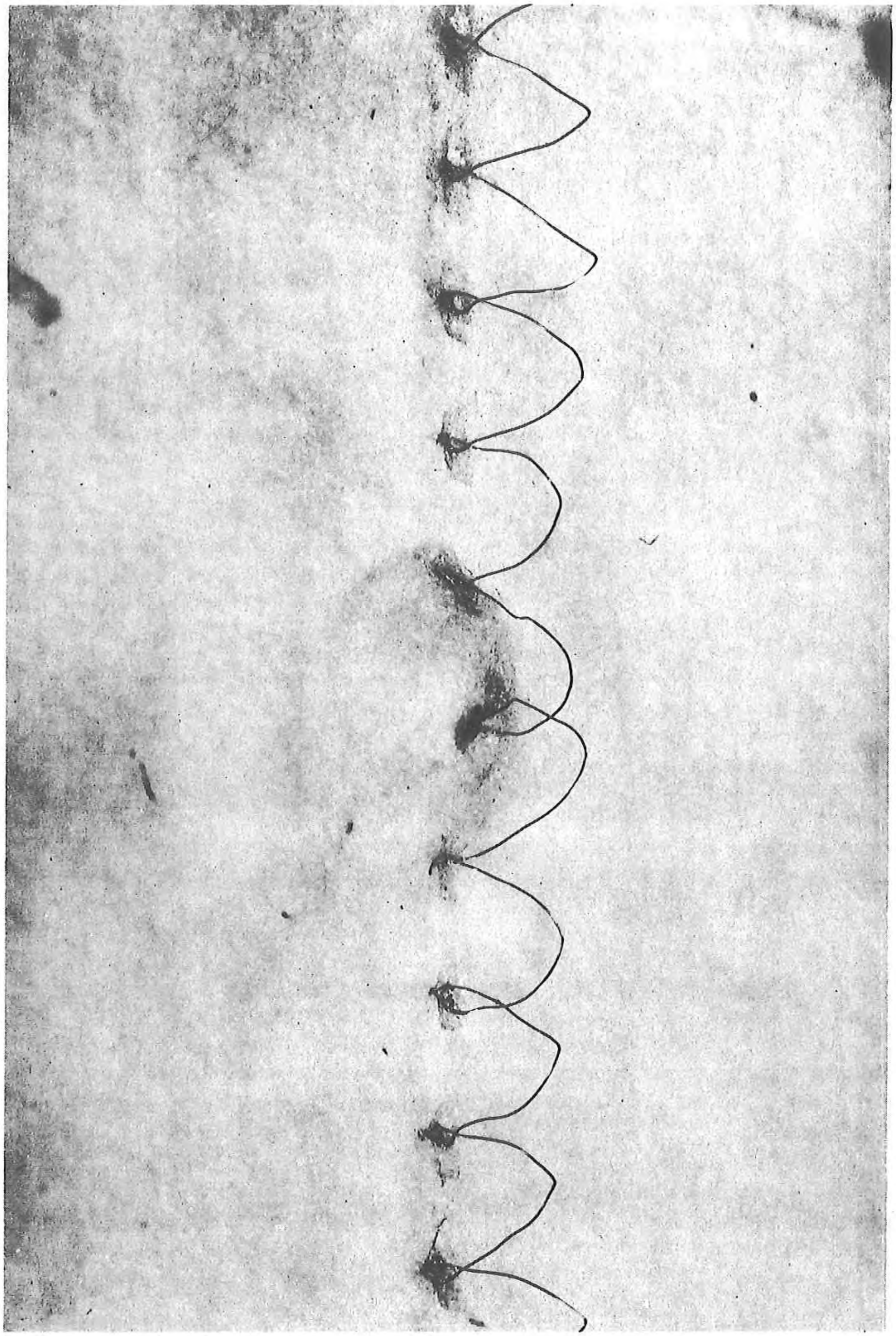

FIGURE 23. ATTACHMENT OF SPARK GAP WIRE TO REAR SURFACE OF NYLON FELT SAMPLE

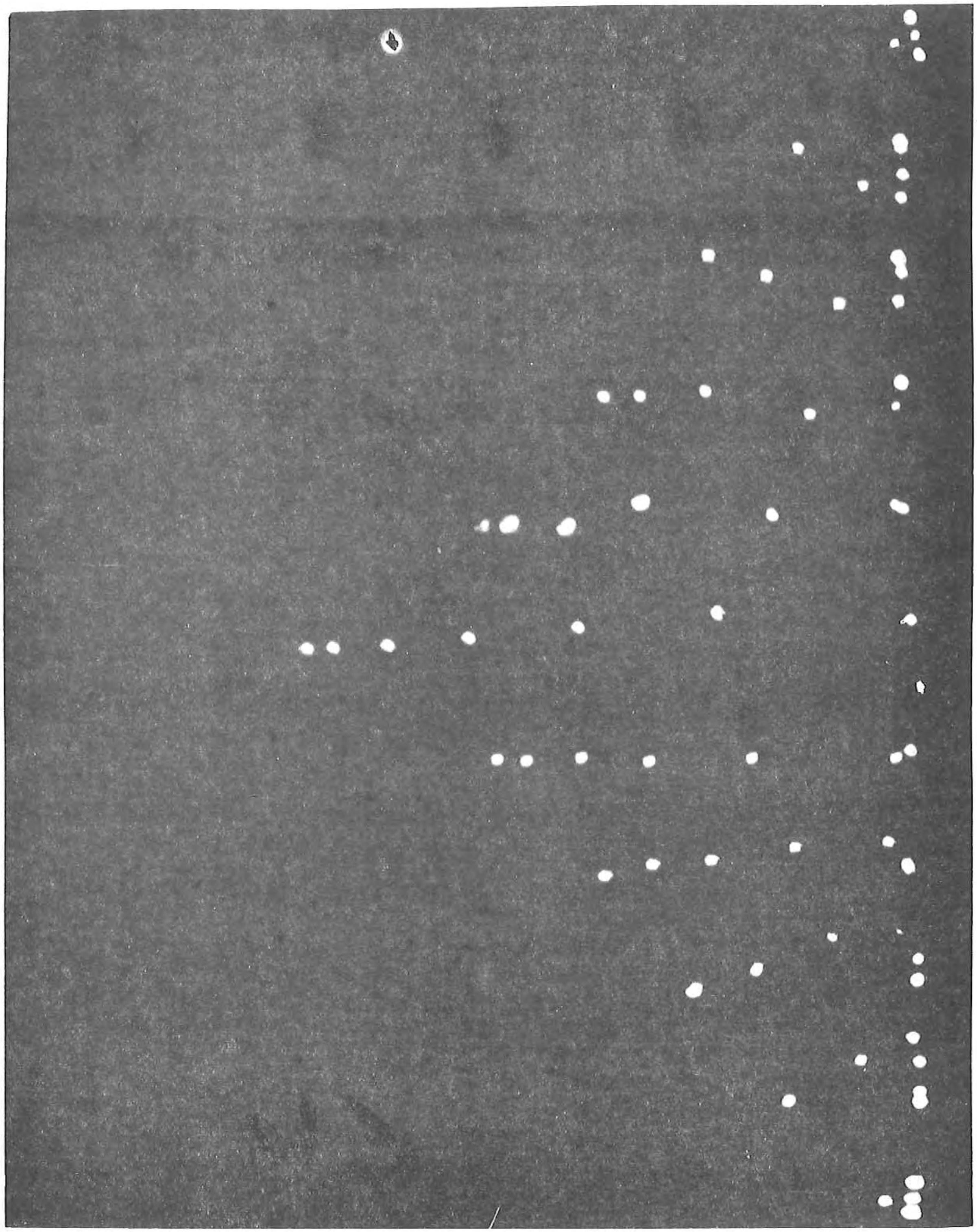

FIGURE 24. PROFILE OF FELT DEFORMATION BY "SPARK GAP" TECHNIQUE

d. Predictive Equations

Based upon a combination of momentum conservation and an assumption of an empirical relationship $V = V_o e^{-KT^3/2}$, a predictive equation was developed by Ipson and Wittrock[16] of the following form:

$$V = \sqrt{\frac{R}{r}}\, V_o e^{\frac{-4/3\pi p^T \quad R}{m_p} \left[(5/4wt)^{3/2} - r^{3/2}\right]} \qquad (2)$$

where: V = velocity of projectile at time t

V_o = initial impact velocity of the projectile at time zero(fps)

V_p = projectile velocity at any time, t (fps)

w = radial transverse wave velocity relative to the r coordinate (fps) = $C_t - u$

C_t = radial transverse wave velocity relative to stationary felt material (fps)

u = radial velocity of felt material imparted by longitudinal wave (fps)

r = radius measured from the axis of the projectile (inches and feet)

t = time after initial contact of projectile and felt material (seconds)

m_p = projectile mass (slugs)

p = mass density of felt material (lb - sec^2/ft^4)

R = radius of .22 caliber fragment simulating projectile (.0183 ft)

T = thickness of the felt material (inches)

In addition to the assumption inherent in positing the exponential empirical relationship between the projectile velocity at any time and the impact velocity, there is also an assumption that the material velocity decays according to the expression suggested by Rinehart:

$$V_r = \sqrt{\frac{R}{r}\ V_p} \qquad (3)$$

Using this equation, prediction of experimental velocity - time data is quite accurate when the impact velocity is half of the V_{50} or less.

The empirical relation

$$V_p = V/_o e^{-K_t{}^{3/2}} \qquad (4)$$

requires knowledge of the term K in terms of material properties. To gain this knowledge requires additional assumptions connecting V_p and V_{zr}; the projectile velocity and the material velocity, respectively, are necessary.

Equation (2) accurately predicts the results when the impact velocity is well below the ballistic limit value. However, as the impact velocity approaches the ballistic limit value, the discrepancy between the prediction of empirical equations and experiments increases sharply. The reason for this is that K was assumed to be a constant dependent only on the parameters of the material. The fact that K may not be constant as the impact velocity approaches the ballistic limit value may well be the reason why the theoretical and experimental data do not agree at this stated limit. This, therefore, leaves the task of establishing the relationship between material parameters and ballistic properties in the region where the impact velocity approaches the ballistic limit value.

The main failure of the model at higher impact velocities may have been due to the felt materials becoming predominantly visco-plastic at the higher stresses and strain rates associated with the higher impact velocities. In any event, it is obvious from many experimental observations that the behavior of felt cannot be approximated by any simple stress-strain relationship. In addition, the degradation of the transverse motion as a function of radius probably is not a simple function of geometry. The absorption of plastic energy probably perturbs this degradation considerably. Future work in this area would have to be based initially upon a two-dimensional system using narrow strips of felt. The three dimensional case is too large a step forward from the yarn analysis conducted by Fenstermaker, Smith, Shiefer, et al. at the National Bureau of Standards(17)(18).

3. Conclusions

As indicated in the Introduction, one of the main goals of this report was to assess the importance of isolatable parameters in ballistic resistant felts. The following sections attempt to summarize this so far as it is possible.

a. Fiber Parameters

(1) Molecular Type. At the present time, experimental evidence favors the polyamide type fibers over all other fiber types.

(2) Molecular Weight. In general, increases in molecular weight improve ballistic performance. Presently available commercial materials are produced at molecular weights of up to 21,000. It can be anticipated that molecular weights even higher than the current 21,000 figure will result in slightly improved ballistic performance. Reduced molecular weights generally lead to reduced tenacity and thus to poorer ballistic performance.

(3) Tenacity. Increased fiber tenacity generally leads to increased ballistic performance in either felt or fabrics.

(4) Molecular Weight Distribution. Little knowledge is available concerning the influence of the molecular weight distribution upon the ballistic performance of the fiber in felt or fabric form. There is considerable potential for improvement of fiber properties by altering distribution of molecular weight since narrowness of distribution is thought to give improved properties to fibers (e.g., higher tenacity). With condensation-type polymers such as the polyamides, inherent difficulties in conducting such a study result from the tendency of the polymer system to revert to the most probable state (where the weight average is double the number average molecular weight).

(5) Crystallinity. The importance of the crystallinity parameters of fibers relative to ballistic performance has not been studied. It is expected that relatively significant improvements may be realized as more knowledge is gained of the size, perfection and orientation of crystalline components in fibrous polymers.

(6) Draw Ratio. Draw ratio currently appears to be more or less maximized (for specific molecular weights of high performance textile materials) in regard to longitudinal strength. Further increases in draw ratio can only be attained by use of higher molecular weight polymers. Higher molecular weights, however, may be difficult to maintain during the transformation from polymer to fiber, and it is problematical whether increased draw ratios will be assured due to complexities such as molecular entanglement.

(7) Elongation. No correlation is presently available between fiber elongation and the resulting ballistic performance of a felt. It can be predicted, based upon very limited experience, that minimum elongation-to-break is more important to the ballistic performance of a felt than to that of a fabric. Most studies, by necessity, have been restricted to fibers having elongations of 20 percent. For example, attempts to prepare felts from low elongation fibers such as glass, polyester, and polyvinyl alcohol have resulted in poor ballistic performance compared to polyamide fibers.

(8) Work-to-Break. There is only very limited correlation of work-to-break of component fibers with the ballistic performance of the resulting felts. A series of fibers of the same family and different work-to-rupture values has yet to be adequately evaluated.

(9) Fiber Surface. Finishes used on polyamide felts generally diminish ballistic performance. Silicones, colloidal silica and polymeric treatments have produced felts with diminished ballistic performance even in cases where the mechanical properties of the felts (e.g., strength) were improved. It is thus concluded that polyamide fibers used in ballistic felts have frictional characteristics very near the optimum and extreme care will be necessary to produce even marginal improvements in ballistics by finishing techniques. Other fiber types may require a finish to realize their ballistic potential because of less than optimal surface characteristics. The use of blends of fibers with different surface characteristics, for example, may offer the possibility of significant improvements in ballistic performance. The greatest potential should be offered by the new industrial procedures for modifying fiber surfaces by chemical modifiers and/or radiation.

(10) Fiber Denier. Past work, specifically on acrylic fibers used in low density felts, has shown that ballistic performance is favored by low denier fibers. In the case of polyamide fibers, appropriate deniers have not been available for a corresponding study, and, therefore, correlation of denier to ballistic performance has not been investigated.

b. Fabrication

(1) Type of Needling. The type of needle is not a primary factor in the improved ballistic performance of a felt.

(2) Density of Needling. Low density needling favors improved ballistic performance.

(3) Angle of Needling. Angle of needling has been found to play an unimportant role in the resulting ballistic performance of a needle-punched felt.

(4) Crimping of Fibers. Anomalous data exist concerning the effect of crimping upon the ballistic performance of a felt. The presence of some crimped fiber is necessary to facilitate production of the felt. Studies have been initiated to determine not only the influence of crimped and uncrimped fibers upon the performance of a felt, but also the role played by the amplitude and frequency of the crimp introduced.

(5) Length of Fibers. In the range from 1/2 inch to 2-1/2 inches the ballistic performance of a felt is directly dependent upon fiber length. Additional increments in fiber length do not significantly improve ballistic performance.

(6) Thickness of Felt. The ballistic performance of a felt, all other factors being equal, is directly proportional to its thickness. The usual pressing operation conducted to attain a thickness of felt amenable to tailoring results in reduced ballistic performance.

(7) Angle of Ply. The angle of ply plays a very minor role in the resulting ballistic performance of a felt.

4. Acknowledgments

The authors wish to acknowledge the contributions of Mr. Elliott Snell and Mr. Hymen Shrager of the Clothing and Personal Life Support Equipment Laboratory, U. S. Army Natick Laboratories, who performed much of the felt work reported. Portions of the work were done on contract, Mr. Rodney Recht and Mr. Thomas Ipson conducted important parts of the dynamic analysis at the University of Denver, while Mr. Robert Keith of the Felters Corporation, Millbury, Massachusetts, Mr. Paul Angelo of Lowell Technological Institute, Lowell, Massachusetts, and Mr. Edgar Rust, of the James Hunter Machine Company, North Adams, Massachusetts, prepared felts under laboratory and plant conditions which were instrumental in acquiring the information outlined.

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13. ABSTRACT

As part of the continuing effort to improve ballistic materials for personnel armor, the fiber and fabrication parameters, dynamics of felt impact, and predictive equations attempting to connect ballistic resistance to known measurable parameters were reviewed for needle-punched felts. The ballistic resistance of needle-punched felts at low areal densities has been found to be superior to that of any other known material. On the other hand, at increased areal densities and against higher velocity missiles, other materials become competitive.

The extent to which needle-punched felts maintain their superiority to other materials at moderate areal densities is dependent upon certain fiber and fabrication properties. The highest tenacity polyamide fibers are currently the best available material. In the case of fabrication, a relatively low degree of needling furnishes the best ballistic properties. In general, the thicker the felt that can be tolerated (at the same weight and areal density), the better the ballistic resistance In addition, it is apparent that the level of ballistic protection varies depending upon the method of attaining the desired thickness.

The need is shown for additional work to determine the effect of fiber properties such as fiber denier, molecular weight, molecular weight distribution, and elongation upon the ballistic properties of the resulting felts. This work, in turn, will depend upon the availability of model fibers in which these parameters can be studied independently.

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Parameters	8		8		8	
Fiber Composites	9		6			
Fibers	9		6			
Fabrication	9		6			
Felts	9		6,9		9	
Needle punched	0		0		0	
Impact strength	8,9		7		7	
Ballistic resistance	8,9		7		7	
Predictive equations			8		8	
Density (mass/volume)			6			
Thickness			6			
Velocity					6	
Missiles					6	